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Program Manager's Questions for LL08-GdNdet-PD03 Development of Large Water-Based Neutron Detectors

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Scientific/Technical Soundness

1. What are the current project goals and are they well defined?

   The basic project goals as outlined in the life cycle plan have not changed significantly. We have three basic goals:

   I. Build a large water based neutron detector, following a similar design to the successful prototype detector built in August 2007 [1]. Though the prototype detected neutrons, there were difficulties with the design and some inefficiencies. We have incorporated some significant upgrades into the new detector design and hope to report that they have been successful.

   II. Test the neutron detection performance of the new detector and test for variations in light output over time from muons traversing the detector.

   III. Test segmentation schemes and water soluble wavelength shifting chemicals in the new detector as ways of maximizing the performance. Detector segmentation may be the best way to deal with the expected increase in the cosmic ray muon rate in our detector, due to the increase in size. The correlated neutron rate will be directly proportional to the rate of nearby cosmic ray muons and will be our most significant background. The detector can be easily configured into three different segmentation regimes. This allows us to veto the detector in sections rather than as a whole, increasing the live-time. Since our detection medium relies on Cerenkov light, we are interested in increasing the photon detection efficiency as much as possible. To this end we will be using our detector and a number of water soluble wavelength shifting chemicals to test their ability to shift invisible UV photons of the Cerenkov spectrum into the (visible) blue.

2. Is the technical program plan reasonable and likely to achieve the project objectives?

   Yes, we believe so.

3. Please describe technical progress to date and indicate how well it meets the agreed to milestone and deliverable schedules.

   Technical progress to date:

   All basic detector parts have been acquired. The DAQ electronics is currently undergoing testing with the PMTs and a full Monte Carlo simulation in GEANT4 has been written (see Melinda Sweany's simulation and electonics presentations). The simulation now awaits tuning with real data. A full technical design of the detector exists. Since the assembly process is fairly complex the design has been a critical part of our problem solving process when putting parts together. A tagged neutron source is being designed, built and tested by a group of senior students at Harvey Mudd for our project. The source will be delivered at the end of this academic year (May 2009). If a source is needed before then we will use a ^{252}Cf source.

Technical Milestone and deliverable schedules:
The schedule written into the life cycle plan called for the detector to be constructed by January 2009 and for fresh water testing to begin soon after. We are probably about two to three months behind that timetable. There are two primary reasons for this delay. Firstly, funding for our experiment was received approximately six months late due to the continuing resolution. Secondly, we have experienced some delays in obtaining laboratory space due to changes in management policies that came into effect in October 2008. Our laboratory space became available in December 2008.

Despite these difficulties, progress has been relatively fast and we are steadily achieving our technical milestones.

4. What additional unresolved technical issues can you anticipate that may potentially cause difficulties?

   We know of no technical issues that would stop our experiment. One technical issue, however, that may cause difficulties is the potting material used on the Hamamatsu PMTs. We ordered the same PMTs used in the Double Chooz experiment. We had no reason to suspect that Hamamatsu would unexpectedly change the potting material; we subsequently discovered the change, after delivery of the parts. The company says that they changed suppliers in order to save costs. If the new potting material, which is black, degrades the transparency of the $GdCl_3$ doped water we will have to remove the PMTs from the detector and coat them in a more benign (clear) plastic or resin, possibly delaying us for a month or two.

5. How have you validated the results of your simulation code, e.g. against the ¼-ton prototype? What is the accuracy of the simulations?

   We have compared the performance of the ¼ ton prototype with simulations. The results were broadly similar. The Monte Carlo prediction for the number of detected photoelectrons was about the same in both cases. The energy resolution was worse in the real detector than the simulation. The lower resolution may have been due to poorer than expected reflectivity from the acrylic/Tyvek walls, which may have increased the signal strength dependence on the directionality of Compton scattered electrons.

We expect the energy resolution to improve in the new four ton detector. We are employing better reflectors on the walls (PTFE), better PMT coverage and a larger detector which will convert a greater proportion of the energy from neutron capture into detectable photons. With better resolution a greater emphasis on simulation tuning should be more meaningful.

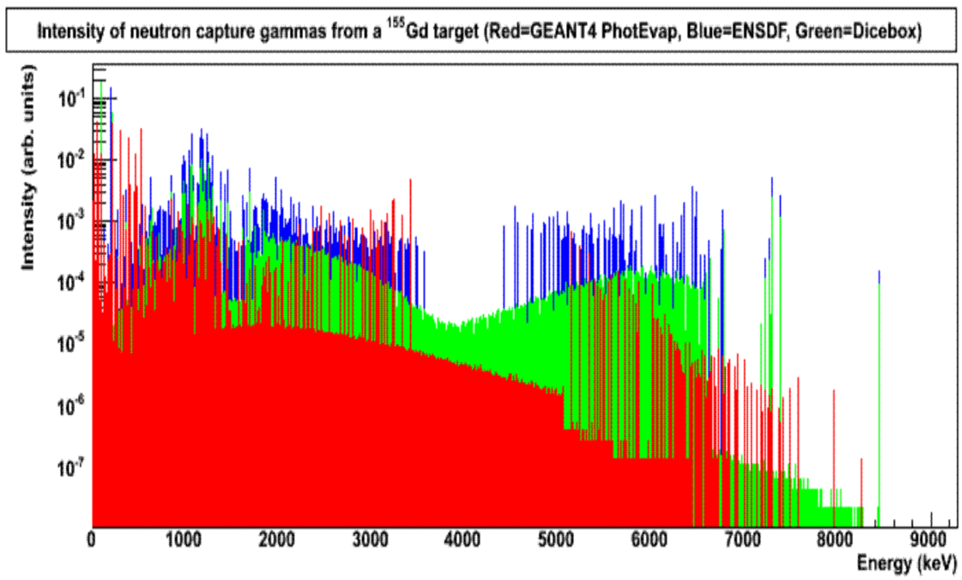
6. How do you determine the optimal Gd concentration in the water?

   The optimal concentration is a compromise between the desire to reduce mean neutron capture times as much as possible (to reduce uncorrelated backgrounds due to gamma-rays from the environment) and the need to ensure light attenuation is minimized. Many simulations of gadolinium loaded detectors have been done for antineutrino detectors. These simulations have been developed over many years and a great deal of work has been done to ensure that they accurately model the neutron capture process. As part of our work on Double Chooz we have investigated the dependence of mean neutron capture times on gadolinium concentration using the “blessed” Double Chooz simulation code. The results of these simulations have not been made public; however, they suggest that the maximum effective concentration, if light transparency is assumed not to decrease, may be about 1%. Higher concentrations do not decrease the neutron capture time further due to the time it takes for neutrons to thermalize. At between 0.5% and 1% concentration the mean capture time begins to saturate at ~10 microseconds. At the time that our life cycle plan was written no study had been done on the attenuation of light due to $GdCl_3$ doping in water. Since then we have published a study which found no increase in attenuation at 0.2% [2], as long as the water doesn’t contact stainless steel. For this reason we plan to test a range of concentrations from 0.2% up to and including 1.0% when the detector is running.

7. What are the energies of the photons in the gamma-ray cascade of Gd? How many have an energy greater than the ~ 2MeV needed for detectable Cerenkov light production?

   The photon energies liberated in a neutron capture on a gadolinium nucleus vary a great deal. In fact, the spectrum of individual photon energies is almost a continuous function up to 8MeV, with a ~1MeV gap near 3 to 4MeV (see figure). The average multiplicity of the cascade is about 5 and energy conservation requires that the total energy of the gamma-ray cascade should add up to 7.9 MeV in the case of ^{157}Gd and

8.5 MeV for ^{155}Gd.   Usually, however, at least one or two high energy gamma-rays are emitted (>~2MeV) per capture.



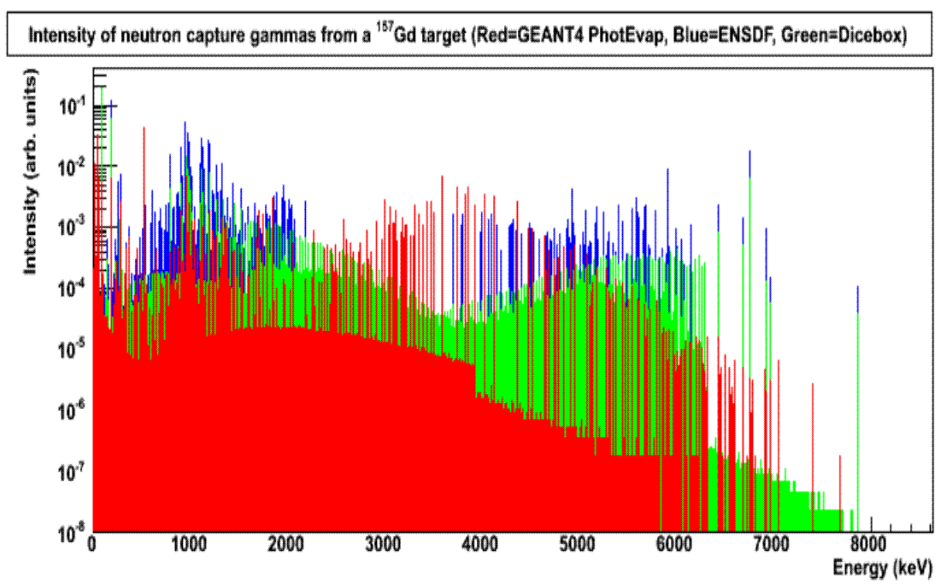


Figure 1: Individual gamma-ray energies emitted from neutron capture on ^{155}Gd and ^{157}Gd. Blue lines are based on real data. Red and green are simulations. Note: simulations do this aspect of neutron capture poorly.

8. What is the impact of escaping gamma-rays on your detection efficiency? How do you mitigate against these losses?

Once a gamma-ray escapes our detector it will evade detection. The only option in our case is to build a larger detector so that a greater proportion of gamma-rays interact inside. Since our four ton detector is 16 times the size of our prototype, a larger fraction of the resulting gamma-rays will interact inside. The overall effect should be a greater separation between the photoelectron signal from neutron capture on gadolinium compared with the background due to low energy gamma-rays from the environment. This will enable us to employ an energy cut to increase our signal to noise ratio.

9. Has the goal of meeting the efficiency of 40% cathode coverage with only 10% coverage and 75% reflectivity been realized?

   This goal will be more than realized in the four ton detector. The photo cathode coverage will in fact be 19%. The walls will have a PTFE layer around the sides. Between the PMTs, we are placing a layer of white polypropylene. Both materials should result in greater than 75% reflectivity. The use of PTFE rather than Tyvek should increase reflectivity in the UV.

10. How will you use reflective coatings, wavelength-shifting plastics, and water additives to reduce backgrounds?

    All of the coatings and wavelength shifting materials we will be testing are designed to increase our energy resolution. Since gamma-ray backgrounds from the environment in our laboratory are generally low energy, mostly either 1.4 MeV (^{40}K) or 2.6 MeV (^{208}Tl), better energy resolution will enable us to more accurately set an energy threshold to reduce these backgrounds. We believe that wavelength shifting materials will increase our resolution in two ways, if it works. Firstly, we will detect more photons. Secondly, reemitted UV light will be isotropic, which will smooth out variations in the detector's energy response with respect to particle direction.

11. What segmentation schemes do you expect will produce the greatest background reductions? Why?

    We do not know. Answering this question is one of the goals of this experiment. At this stage we have not conducted a serious study into the likely reduction in neutron backgrounds versus segmentation scheme. We are waiting until we have tuned our simulation code to reproduce the detector response before conducting an in depth study.

12. How do you make multiplicity measurements? What is the temporal and/or spatial resolution? When do multiple events appear as one? What is the impact of the reflector on multiplicity measurements?

The use of reflecting walls will severely limit our spatial resolution. This is one of the reasons for employing a segmentation scheme – so that some spatial knowledge can be used to discriminate against backgrounds. The temporal resolution can be as fast as the electronics will allow. Our electronics will be limited by a bandwidth of approximately 100 MHz, allowing for a temporal resolution of ~10 nanoseconds. We won't be able to make multiplicity measurements of neutron capture gamma-rays, however, we will be able to detect multiple neutrons if the efficiency is high enough.

13. Please present an outline of your test plan for the 4-ton detector.

Our test plan to achieve the goals outlined in question (1) is as follows:

1) Fill detector with fresh deionized water. Test the detector electronics and equalize PMT gains. Measure detector response to the passage of cosmic ray muons. This will serve as a baseline for our tests of wavelength shifting chemicals later in the testing program. We will also measure the neutron capture spectrum for capture on hydrogen to compare later with our gadolinium results.
2) Fill detector with $GdCl_3$ at same concentration as the prototype detector (0.2%). Compare with performance of prototype ¼ ton detector. Measure the neutron capture energy spectrum and neutron detection efficiency using the Harvey Mudd tagged neutron source at various positions inside and outside the detector. Also measure the neutron capture time. Use the muon energy spectrum to regularly measure the relative effects on water clarity over time. This measurement will give us an indication of how often the water will need to be replaced in an operational detector.
3) Measure the signal to background rate with different segmentation schemes.
4) Fill detector with higher $GdCl_3$ concentrations (up to ~1.0% if possible). The performance of the PMTs in this harsh environment will be monitored carefully. At any sign of trouble the concentration will be dropped back. Measure the neutron capture spectrum and capture times with respect to $GdCl_3$ concentration. Again measure the muon spectrum.
5) At the optimum level of $GdCl_3$ concentration we will attempt to increase the photon detection efficiency with chemical wavelength shifters. Tests performed for SNO. [3] and at UC Davis (See Svoboda's talk) have already identified some promising chemicals that we can experiment with. With each chemical we will attempt to measure the neutron capture performance and the muon energy spectrum.

Management/Execution

1. Who are the primary individuals working on this project and what are their roles? Please include any university or other subcontractors as they are instrumental to the success of this project. Please provide the background of these individuals relevant to their roles.

 There are three institutions involved at some level in this project. Lawrence Livermore National Laboratory (LLNL) is the primary institution. UC Davis and Harvey Mudd College also collaborate with us on this project.

 At LLNL the people involved with the project are:

 Steven Dazeley – PI, actively involved in all aspects of the project. Steven obtained a PhD in gamma-ray astrophysics from the University of Adelaide (Australia) in 2000. Since then he was a postdoc under Rober Svoboda at LSU, working on the KamLAND, Super-Kamiokande and Double Chooz neutrino projects. Steven joined LLNL in 2006 and has since joined the LUX dark matter collaboration and the SONGS antineutrino project.

 Adam Bernstein – Adam is leader of the Advanced Detectors Group in Physics Division. He has a Ph.D in experimental high energy physics from Columbia University and an undergraduate degree in physics from UC Berkeley. With regard to the current project, he has helped design the detector, has identified potential nuclear security applications of the technology, and been instrumental in writing proposals and securing of funding for this and related work. He specializes in applying methods and detection technologies from high energy and nuclear physics to nonproliferation, arms control and nuclear security problems. He holds a patent (with 5 co-authors) for a 'nuclear car wash' active detection system based on beta-delayed fission gamma-rays, an area where water based neutron/gamma detection may offer advantages. His work on detector development for active screening of cargo for SNM received a science and technology award from LLNL in 2006, the most exclusive scientific award at the lab, and was cited in Discover magazine as one of the top 100 most significant scientific stories in that year.

 Robert Svoboda – Was the original PI for this project and in his capacity as a LLNL staff scientist has primarily been involved with detector design. Robert is a very experience neutrino physicist who has worked on IMB, Super-K, KamLAND and Double Chooz. He is now the US spokesman for Double Chooz and is also leading the effort to build a megaton water Cerenkov detector in the DUSEL underground laboratory in South Dakota. He is also a leading member of the LUX dark matter collaboration.

 Serge Ouedraogo – Serge is a postdoc from LSU who joined our group in late December 2008. Serge obtained his PhD from LSU in neutrino physics, working on the MiniBoone detector. As part of his work on the MiniBooNE experiment, he developed and maintained a laser system used for calibration purposes. For his thesis analysis, he developed a statistical method to search for the muon neutrino magnetic moment for neutrino energy between 15 and 100 MeV.

UC Davis

Robert Svoboda – As a UC Davis professor Robert coordinates collaboration between our group and UC Davis. He is also working on R&D into water soluble wavelength shifting chemicals. This work may have a direct impact on the performance of our detector

Melinda Sweany – Melinda is a graduate student from UC Davis. Her involvement stems from her interest in the development of an active neutron shield for LUX. As such her work on our project is Research for LUX.

John Felde – John is a graduate student working with Robert Svoboda and is also investigating a number of wavelength shifting, water soluble chemicals.

Harvey Mudd College

Richard Haskell – Professor Haskell supervises a group of senior undergraduate students developing a tagged neutron source for our detector at Harvey Mudd. Professor Haskell has worked on a number of successful projects with us in the past.

The undergraduate students working on this project are Rachael Martin, Jonathan Hubbard, Elizabeth Ellis and Reuben Villagomez.

2. Is there any potential for small business collaboration for any components of this project (potentially funded though our SBIR programs)?

   The long term potential is there, but we have not yet actively pursued any SBIR collaborations. At this stage of technology development, such collaboration is probably premature. Once we have a clearer idea of the practical design parameters and specific applications for this detector technology, it might make sense to seek an industrial partner. We have submitted a Record of Invention at LLNL for this detection concept, a necessary precursor to a patent and to finding a corporate partner.

3. Is this project team engaged in similar work sponsored by DNDO, DTRA, or other NNSA offices? If so, please describe technical area and application area.

   Yes. The ¼ ton prototype (developed before our 4 ton detector) was initially conceived as an antineutrino detector for another NA-22 project

(LL08 ARM094-PD02). The application of this project is to develop technologies to cooperatively monitor plutonium production in real time at a commercial nuclear reactor site (the SONGS reactor in San Clemente, California).

We also have a 2 year DUSEL R&D grant from DOE-HEP (non-NNSA) to develop active shields for dark matter detectors, and to measure attenuation lengths and stability of Gd-doped and WLS-doped water for use in very large Water Cerenkov Detectors.

4. Is this project team engaged in similar work sponsored by other WFO or IWFO? If so, please describe how the technical work is complementary and integrates into this NA-22 sponsored effort. Please be sure to upload and properly account for all reports or publications generated by this project into webPMIS?

   The DOE projects above are the only ones related to this work.

5. Who are competitors for developments of this or similar technology in the labs, universities, and industry and how are you distinguishing yourselves from them?

   No other group (as far as we know) is developing water Cerenkov technology for nuclear non-proliferation and nuclear security purposes. There are, however, competing technologies and techniques being developed or already in use.

   In general in this and other areas of nonproliferation and nuclear security, we expect to distinguish ourselves by virtue of the unique combination of low cost, low environmental impact, large solid angle coverage, good efficiency and good background rejection properties that the water detectors may provide. We provide a brief comparison with deployed systems and others in the R&D phase.

   Currently deployed systems: For passive screening of traffic for nuclear materials, plastic scintillator combined with a few He3 detectors is the most common approach at U.S. borders. These systems are rate counters only, and are not sensitive to the multiplicity events that are known to be a distinguishing feature from SNM. Large solid angle sensitivity to a correlated neutron signal might allow for greater specificity for SNM in passive screening deployments.

Passive systems in the R&D phase: At LLNL and elsewhere, ton-scale multi-detector suites (He3, plastic and liquid detectors) have been used to study passive detection of SNM in various contexts The detector proposed here is less sensitive to <2.6 MeV gamma-rays and the high energy neutron recoil signals that can degrade the performance of liquid scintillator detectors, and could be deployed at lower cost than the large arrays of He3 tubes that would be needed for the target solid angle coverage goals of ~1π to 2π.

Active systems in the R&D phase: Concerning active SNM detection methods, an LLNL group [4] has developed large plastic and liquid scintillator prototype detectors for measuring the high energy (3-10 MeV) beta-delayed fission gammas from neutron-irradiated SNM in cargo. Here the main advantage of our approach is cost, the simplicity of a single detector type, and insensitivity to both cosmic ray fast neutrons and to <2.6 MeV gamma rays.

<u>Potential User Impact</u>

1. What end user agencies with non-proliferation, counter-proliferation, or counter-terrorism applications might be expected to be interested in the capabilities of the technology being developed in this effort? What contacts, if any, have been made with these organizations and have they shown an interest or made suggestions?

   We have not yet directly approached end users with this technology, but the need for large solid angle and low cost neutron and gamma detection is a top priority within the NA-22 roadmap for SNM detection, which document was closely informed by discussions with end users. Possible end users include homeland security for passive or active screening of cargo or luggage, nonproliferation agencies such as IAEA, US agencies, including DOE and DHS that have responsibility for assisting foreign screening and interdiction efforts at borders and nuclear facilities.

References:
[1] "Observation of Neutrons with a Gadolinium Doped Water Cerenkov Detector", A S. Dazeley, A. Bernstein, N. S. Bowden, R. Svoboda, submitted to Nuclear Instruments and Methods, arXiv:0808.0219, 2008.
[2] "Transparency of 0.2% GdCl3 Doped Water in a Stainless Steel Test Environment", W. Coleman, A. Bernstein, S. Dazeley, R. Svoboda, Nuclear Instruments and Methods, A595:339-345,2008

[3] “Wavelength shifters for water Cherenkov detectors”, Nuclear Instruments and Methods Section A V589, P 290, 2008
[4] “The nuclear car wash: A system to detect nuclear weapons in commercial cargo shipments”, D. R. Slaughter et. al., Nuclear Instruments and Methods Section A, V579, P 349, 2007